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Snow cover phenology affects alpine vegetation growth dynamics on the Tibetan Plateau: Satellite observed evidence, impacts of different biomes, and climate drivers

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ABSTRACT

Alpine vegetation plays a crucial role in global carbon cycle. Snow cover is an essential component of alpine land cover and shows high sensitivity to climate change. The Tibetan Plateau (TP) has a typical alpine vegetation ecosystem and is rich of snow resources. With global warming, the snow of the TP has undergone significant changes that will inevitably affect the growth of alpine vegetation, but observed evidence of such interaction is limited. In particular, a comprehensive understanding of the responses of alpine vegetation growth to snow cover variability is still not well characterized on TP region. To investigate this, we calculated three indicators, the start (SOS) and length (LOS) of growing season, and the maximum of normalized difference vegetation index ($NDVI_{max}$) as proxies of vegetation growth dynamics from the Moderate Resolution Imaging Spectroradiometer (MODIS) data for 2000–2015. Snow cover duration (SCD) and melt (SCM) dates were also extracted during the same time frame from the combination of MODIS and the Interactive Multi-sensor Snow and Ice Mapping System (IMS) data. We found that the snow cover phenology had a strong control on alpine vegetation growth dynamics. Furthermore, the responses of SOS, LOS and $NDVI_{max}$ to snow cover phenology varied among different biomes, eco-geographical zones, and temperature and precipitation gradients. The alpine steppes showed a much stronger negative correlation between SOS and SCD, and also a more evidently positive relationship between LOS and SCD than other types, indicating a longer SCD would lead to an earlier SOS and longer LOS. Most areas showed positive correlation between SOS and SCM, while a contrary response was also found in the warm but drier areas. Both SCD and SCM showed positive correlations with $NDVI_{max}$, but the relationship became weaker with the increase of precipitation. Our findings provided strong evidence between vegetation growth and snow cover phenology, and changes in snow cover should be also considered when analyzing alpine vegetation growth dynamics in future.

1. Introduction

During the past three decades, the Northern Hemisphere has very likely experienced the warmest 30-year period on the record (IPCC, 2014). Such abrupt warming can affect many aspects of vegetation, such as plant composition and diversity, phenology, productivity, biomass, and vegetation fraction (Liu et al., 2017; Ozanne et al., 2003; Thomey et al., 2011; Thompson et al., 2015; Wu et al., 2016; Zhang et al., 2010). These changes in vegetation may also feedback to climate system (Zhao et al., 2006). High latitude and altitude ecosystems such as alpine regions are facing the greatest warming. As an important component of terrestrial ecosystem, alpine vegetation plays a crucial role in seasonal carbon, water, and energy cycles (Inouye and Wielgolaski, 2013; Körner, 2005; Shen et al., 2015). Thus, investigating the responses of alpine vegetation to global warming is of great significance for understanding the global climate change.

In alpine regions, snow is a major source of fresh water for vegetation activities (Beniston et al., 1997). Furthermore, snow cover

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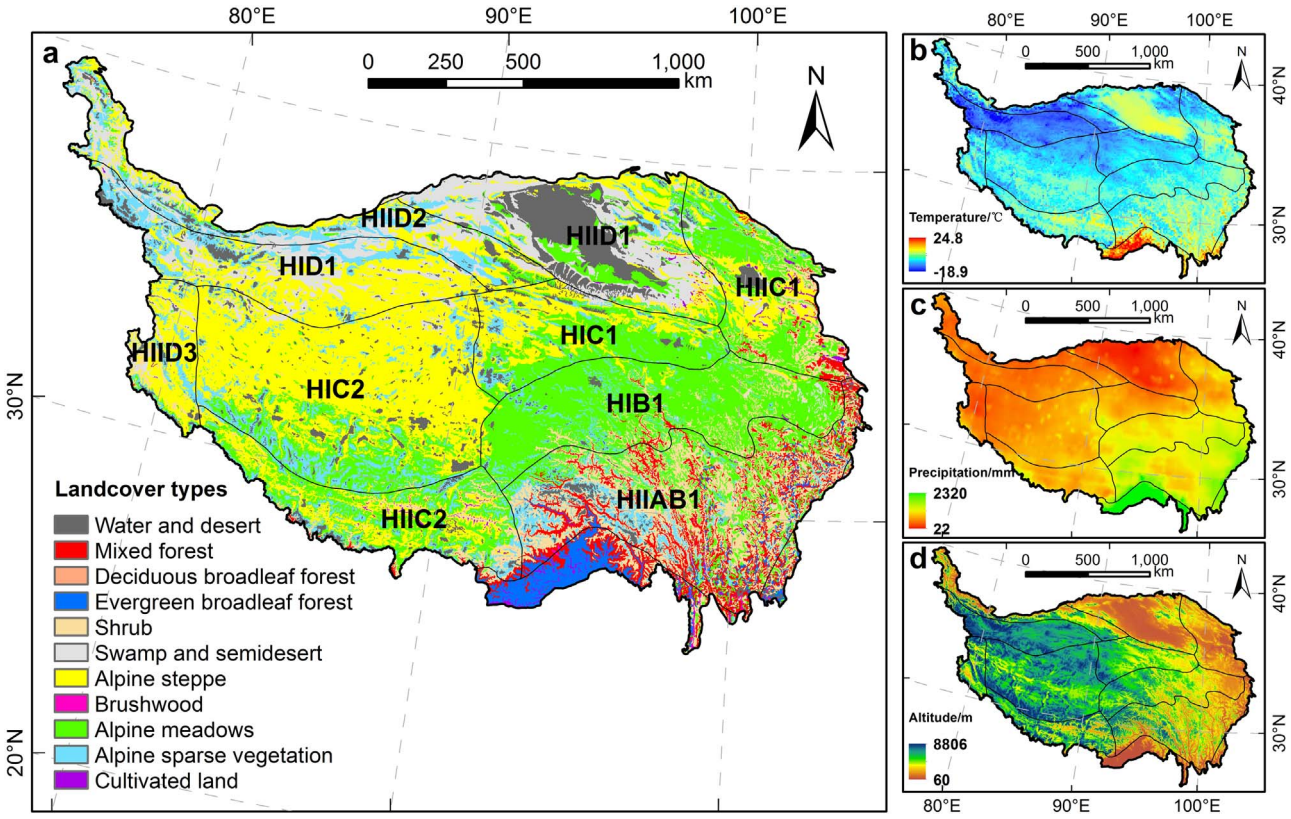

Fig. 1. Description of the (a) land cover types and eco-geographical zones, (b) annual mean temperature, (c) annual total precipitation, and (d) elevation of the study area.

protects soil from wind and low temperature, which is beneficial to the growth of vegetation (Nobrega and Grogan, 2007). Although the response of snow cover to global warming is complicated, as snow formation and melt are closely related to a temperature threshold of 0 °C, snow cover is the most predictable climate indicator among several other land, ocean, and cryosphere climate variables (Gonsamo et al., 2016b). With global warming, snow cover has significantly changed as evidenced from multiple in-situ observations and satellite data (Chen et al., 2015a; Gonsamo et al., 2016b; Peng et al., 2013). Previous studies have shown that changes in snowpack could alter energy flow and water cycle, which has significant implications on vegetation growth. Buus-Hinkler et al. (2006) analyzed the relationship between the normalized difference vegetation index (NDVI) and snowmelt date in Northeast Greenland through digital camera images. Their results revealed that vegetation vigor was linked to the initiation time of the snow-free period rather than air temperature. Groffman et al. (2001) also suggested that the decrease in snowpack, as may occur in a warmer climate, would result in the increase in soil freezing and cause microbial mortality, hydrologic and gaseous losses of nitrogen, which could impact vegetation growth. Paudel and Andersen (2013) analyzed the response of rangeland vegetation to snow cover dynamics and suggested that snow cover phenology played more important roles in snow-fed and drier regions for vegetation phenology.

The Tibetan Plateau (TP), the largest and highest plateau on the Earth, is regarded as the third pole of the Earth. There are typical alpine vegetation ecosystems and abundant snow resources on the plateau. Moreover, due to its fragile and instable ecosystems and natural environment, TP is believed to be more vulnerable to global warming (Wang et al., 2017b). Thus TP is an ideal area for investigating the snow cover effect on vegetation activities. The TP has experienced significant warming trends over the past three decades. In parallel to this warming signal, snow cover has changed significantly and may influence runoff amounts and spring time land surface phenological trend over this region (Wang et al., 2013). In recent years, site level experiments were conducted on a specific vegetation type or in a small area of TP to describe the interrelation between vegetation dynamics and snow cover (Chen et al., 2014; Chen et al., 2008). These conclusions are important but cannot be deemed representative of the whole area. Other studies like Wan et al. (2014), investigated the impact of snow depth, retrieved from passive microwave data, on alpine vegetation over the whole plateau. However, the coarse spatial resolution of microwave data (25 km) cannot sufficiently reflect the interior heterogeneity of such influence given the complex geographical features of TP. Wang et al. (2017a) analyzed the response of spring phenology to snow cover dynamics on the TP. However, only the spring phenology cannot adequately reflect the condition of alpine vegetation growth, and the driving mechanisms of different response need to be further explored.

Based on the Moderate Resolution Imaging Spectroradiometer (MODIS) 500 m data during 2000–2015, we first calculated the start of growing season (SOS), the length of growing season (LOS) and the maximum of NDVI ($NDVI_{max}$) as the main indicators of growth dynamics of alpine vegetation. Snow cover duration (SCD) and snow cover melt date (SCM) were also determined from MODIS and IMS data to represent the snow cover phenology variability. We then examined spatial variability in the responses of SOS, LOS and $NDVI_{max}$ to SCD and SCM over the whole plateau. Correlations in different biomes, eco-geographical zones, and temperature and precipitation gradients were also investigated to better understand the dependence of such impacts. The overall questions we address are whether the phenological changes of snow cover can affect the growth of vegetation dynamics on the TP, and how such influence varies by biomes and climate drivers in a spatially explicit way over the vast areas.

2. Data and method

2.1. Study area

The Tibetan Plateau (TP) is located in the southwest of China

Table 1
Eco-geographical zones of the Tibetan Plateau.

Temperature zone		Humidity region		Eco-geographical zone	
HI	Plateau sub-cold zone	B	Sub-humid zone	HIB1	Golog-Nagqu high-cold shrub-meadow zone
		C	Semi-arid zone	HIC1	Southern Qinghai high-cold meadow steppe zone
				HIC2	Qangtang high-cold steppe zone
		D	Arid zone	HID1	Kunlun high-cold desert zone
HII	Plateau temperate zone	A/B	Humid/sub-humid zone	HIIA/B1	Western Sichuan-eastern Tibet montane coniferous forest zone
		C	Semi-arid zone	HIIC1	Eastern Qinghai-Qilian montane steppe zone
				HIIC2	Southern Tibet montane shrub-steppe zone
		D	Arid zone	HIID1	Qaidam montane desert zone
				HIID2	Northern slopes of Kunlun montane desert zone
				HIID3	Ngari montane desert zone

(26°00′12″N–39°46′50″N and 73°18′52″E–104°46′59″E, Fig. 1). It is also called "the Roof of the World" and is the highest and largest plateau in the world, with an average elevation exceeding 4000 m and an area of approximately 2.5×10^6 km^2. Due to its low latitude and high altitude, The TP has strong solar radiation and long sunshine hours. Influenced by elevation and the Indian Ocean monsoon (Chen et al. 2015b), the climate on the plateau is characterized by a moisture and heat gradient from southeast to northwest. The TP has a unique climatic condition, and thus forms a typical alpine vegetation ecosystem including alpine steppes (27.9%), alpine meadows (25.6%), alpine sparse vegetation (11.7%), and shrub (10.6%) (Fig. 1a). Snow cover over the TP is a vital fresh water source in western China, and is closely related to biological and hydrological processes in the TP and its surrounding areas (Tang et al., 2013). The unique geographical conditions of TP create unique ecological environment characteristics of the plateau. Therefore, to better investigate the spatial patterns of vegetation growth and snow cover phenology, and their relationship, we divided the TP into ten eco-geographical zones (Table 1, Fig. 1) based on the thermal conditions, moisture regimes and topographic features (Wu et al., 2003).

2.2. Datasets

The MODIS based NDVI datasets MOD13A1 (Collection 6), with a 500 m spatial resolution and 16day intervals, were used to determine vegetation phenology from 2000 to 2015 over the TP. The datasets were generated based on a series of sophisticated algorithm and strict quality control (Justice et al., 1998). This product was obtained from the Atmosphere Archive Distribution System Distributed Active Archive Center (LAADS DAAC, https://ladsweb.nascom.nasa.gov).

The snow cover phenology was calculated by combining three different snow cover datasets: two MODIS daily snow products MOD10A1 and MYD10A1 (Version 5), and the IMS data. The overall accuracy of MODIS daily snow products can reach 90% in clear sky condition (Ault et al., 2006), and IMS data can provide snow information regardless of cloud interference. All these snow cover datasets for the TP can be downloaded from the National Snow and Ice Data Center (NSIDC, http://nsidc.org).

Monthly mean temperature and total precipitation of the TP were calculated from the China Meteorological Forcing Dataset acquired from Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn). The Digital Elevation Model (DEM) data was obtained from SRTM 90 m Digital Elevation Database from CGIAR Consortium for Spatial Information (CGIARCSI, http://www.cgiar-csi.org).

2.3. Preprocessing of NDVI data

In seasonally snow-covered regions, changes in snow cover would influence NDVI time-series, which can confound the derivation of land surface phenology (Delbart et al., 2006; Thompson et al., 2015). In order to eliminate this effect, we replaced the snow-contaminated NDVI values with the median value of the uncontaminated NDVI values during the non-growing season (Shen et al., 2014). Furthermore, cloud contamination can result in abnormal values in the vegetation indices and may also influence the determination of vegetation phenology (Ding et al., 2015). Therefore, the SavitzkyGolay filter was used to smooth the NDVI time series (Chen et al., 2004). To focus on the areas with vegetation and seasonality, pixels were selected for further analysis based on the following three criteria. First, the multiyear average NDVI should be higher than 0.1, because areas with much lower mean NDVI were usually regarded as bare soil or sparsely vegetated regions (Jeong et al., 2011). Second, the annual maximum NDVI should occur between July and September. Third, the average NDVI for July–September should be 1.2 times higher than the average NDVI for November–March (Shen et al., 2014).

2.4. Determination of vegetation phenology

A series of piecewise logistic functions were used to fit the NDVI data. NDVI time series were divided into two sections by the time of annual maximum NDVI in each year, and a four parameter logistic function, which was developed by Zhang et al (2003), was applied to fit each section:

$$y(t) = \frac{c}{1 + e^{a+bt}} + d \tag{1}$$

where t is the day of year (DOY), $y(t)$ is the NDVI value at time t, a and b are fitting parameters, $c + d$ is the maximum NDVI value, and d is the initial background NDVI value (Zhang et al., 2003). Then, the rate of change in the curvature K' was calculated according to Eq. (2):

$$K' = b^3 cz \left\{ \frac{3z(1-z)(1+z)^3[2(1+z)^3 + b^2c^2z]}{[(1+z)^4 + (bcz)^2]^{\frac{5}{2}}} - \frac{(1+z)^2(1+2z-5z^2)}{[(1+z)^4 + (bcz)^2]^{\frac{3}{2}}} \right\} \tag{2}$$

where $z = e^{a+bt}$. We then defined SOS and EOS as the time when K' reached its first and last local maximum values, respectively (Fig. 2). The length of the growing season (LOS) is defined as the time span between SOS and EOS.

2.5. Calculation of snow cover phenology

To calculate the snow cover phenology accurately, cloud pixels should be removed from the original MODIS snow cover products. First, MOD10A1 and MYD10A1 were combined to reduce the proportion of cloud covered pixels. Second, data of three successive days were further combined, and data of the prior day or the subsequent day was chosen to replace the cloud pixel if cloudfree conditions can be found in the two observations. Third, IMS data was used to remove all remaining cloud pixels (Wang et al., 2017c). Then snow cover duration (SCD), and melt date of snow cover (SCM) were calculated as described in Wang

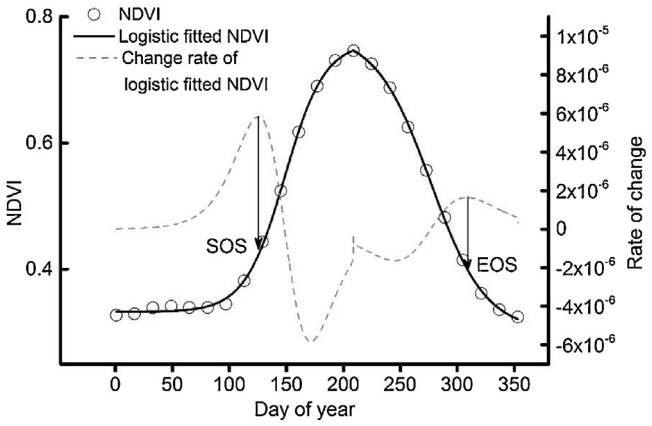

Fig. 2. A schematic showing how the start (SOS) and end (EOS) of growing season were detected using the method developed by Zhang et al. (2003).

and Xie (2009) with equations below:

$$SCD = \sum_{i=1}^{n} s_i \tag{3}$$

$$SCM = Fd + SCD_{aFd} \tag{4}$$

where, n is the total number of days within a hydrological year (1 September to 31 August of the next year), s_i is occurrence of snow cover, with values 1 for snow and 0 for no snow, Fd is a fixed date, and SCD_{aFd} is the SCD after Fd. The snow cover over the TP begins to melt in spring (Pu et al., 2007; Wang et al., 2015b). Therefore, we set Fd to 1st of march.

2.6. Statistical analyses

To investigate the relationship between vegetation growth and snow cover, we calculated the Pearson's correlation coefficients between snow cover phenology and SOS, LOS, as well as $NDVI_{max}$. In addition, we performed a t-test to reflect the significance level (p-value) of the relationship. We first examined the correlations in each pixel to reflect their spatial patterns. Then we selected the pixels with significant correlations ($P < 0.1$) to further investigate the relationships among different biomes, eco-geographical zones, and hydrothermal gradients.

The vegetation cover characteristics were based on the Vegetation Atlas of TP, which was obtained from Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. Since more than 90% vegetated area consists of alpine steppes, alpine meadows, alpine sparse vegetation, and shrub on TP, we focused on the relationships between snow cover phenology and vegetation growth for these four main biomes.

Temperature and precipitation may be the major drivers in controlling the response of vegetation growth to snow cover phenology. So we divided the annual total precipitation into 25 zones with an interval of 50 mm over the whole plateau. We further divided each precipitation zone into 22 sub-zones along the annual mean temperature gradient with an interval of 1 °C. The relationship between SCD and SOS, SCM and SOS, SCD and LOS, SCM and LOS, SCD and $NDVI_{max}$, and SCM and $NDVI_{max}$ were then examined for each zone. To avoid the mixed impacts from different biomes and climate factors, we analyzed the climate controls for each of the four main biomes separately.

3. Results

3.1. Spatial patterns of SOS, LOS and $NDVI_{max}$

Spatial patterns of SOS, LOS and $NDVI_{max}$ were described by their mean values and the standard deviation (sd) over the study period (Fig. 3). Generally, SOS showed an increasing trend from east to west, while both LOS and $NDVI_{max}$ decreased from east to west. The SOS mainly occurred from 120 to 170 day of year (DOY), accounting for 94.0% of the study area. The eastern border of the plateau had early SOS, with occurrence DOY before 120 (May 1st). The regions with later SOS, occurring in middle of June, were mainly located in the southwestern borders. However, a small area in the northwestern edge showed earlier SOS around early May. Overall, most regions (78.2% of the plateau area) had low sd of SOS within 15 days over the study period. Regions with sd of SOS between 15 and 30 days comprised about 13.7%, and the percentage of sd of SOS higher than 30 days was found only in 8.1% of the plateau area. LOS in most regions (82.8%) ranged from 120 to 150 days. LOS was longer than 170 days in east TP and shorter than 120 days in the west part. Most areas (88.0%) had sd of LOS within 15 days. $NDVI_{max}$ showed a similar spatial pattern as LOS. The eastern part of TP had the highest $NDVI_{max}$, mostly above 0.8. The $NDVI_{max}$ decreased to 0.4–0.6 in the central plateau, and reduced to less than 0.3 in the western part. Most regions in the east and west of the plateau had low sd of $NDVI_{max}$ within 0.03, and the highest sd were found in the northeastern part (more than 0.08). Several areas in the central and southwestern part of the plateau also had high sd of about 0.07.

3.2. Spatial patterns of snow cover phenology

A substantially large region of TP was covered by snow but it was unevenly distributed due to heterogeneity in local climatic and topographic factors (Fig. 4). Regions that had long SCD were mainly located at the northwest edge and southern part of the TP while SCD was shorter in the vast interior areas except for places with high mountains. Regions with the shortest SCD (less than 10 days) were found in the south of Nyainqentanglha Mountains, the river valleys of southern Tibet, Qangtang area, Qaidam Basin and south regions of Qilian Mountains. We thus defined these regions as snow-free areas, which were excluded in later analysis. Overall, 60.7% of the study area had low sd of SCD within 20 days, and the percentage of sd higher than 40 days occurred only in 5.3% of the plateau area. The spatial pattern of SCM was similar to SCD. Regions with high elevation had the latest SCM dates, while SCM overall occurred earlier with the decrease of elevation. Specifically, SCM was later than April 30th (DOY 120) in the western borders of the TP. In the vast interior of the plateau, SCM occurred between late March and middle April. Most regions had small sd of SCM within 12 days and the regions with the largest sd (more than 21 days) were located in the south border of the TP.

3.3. Response of SOS to snow cover phenology

Fig. 5a and b show the relationship between SCD and SOS, and we found that about 13.8% of the area had significant relationships between these two indicators ($P < 0.1$). We found a significant negative correlation in the northeastern and central part and southwestern edge of the TP, indicating that a longer duration of snow cover in winter could advance SOS in the following year. However, more snow cover may also delay SOS, which was evidenced in the positive correlation in small regions of eastern TP. The pixel-wise correlation analysis showed that SOS and SCM was significantly correlated for about 15.4% of the study area (Fig. 5c and d). Most regions in the central plateau (9.5%) had a positive relationship, which means that SOS would be delayed with a later snow cover melting. In addition, we also observed a contrary effect of SCM on SOS, and several regions in the northeast and southwest of the TP showed advanced SOS with later SCM.

3.4. Response of LOS to snow cover phenology

LOS was also influenced by snow cover phenology (Fig. 6). 11.0% of the study areas showed a significantly positive correlation between SCD

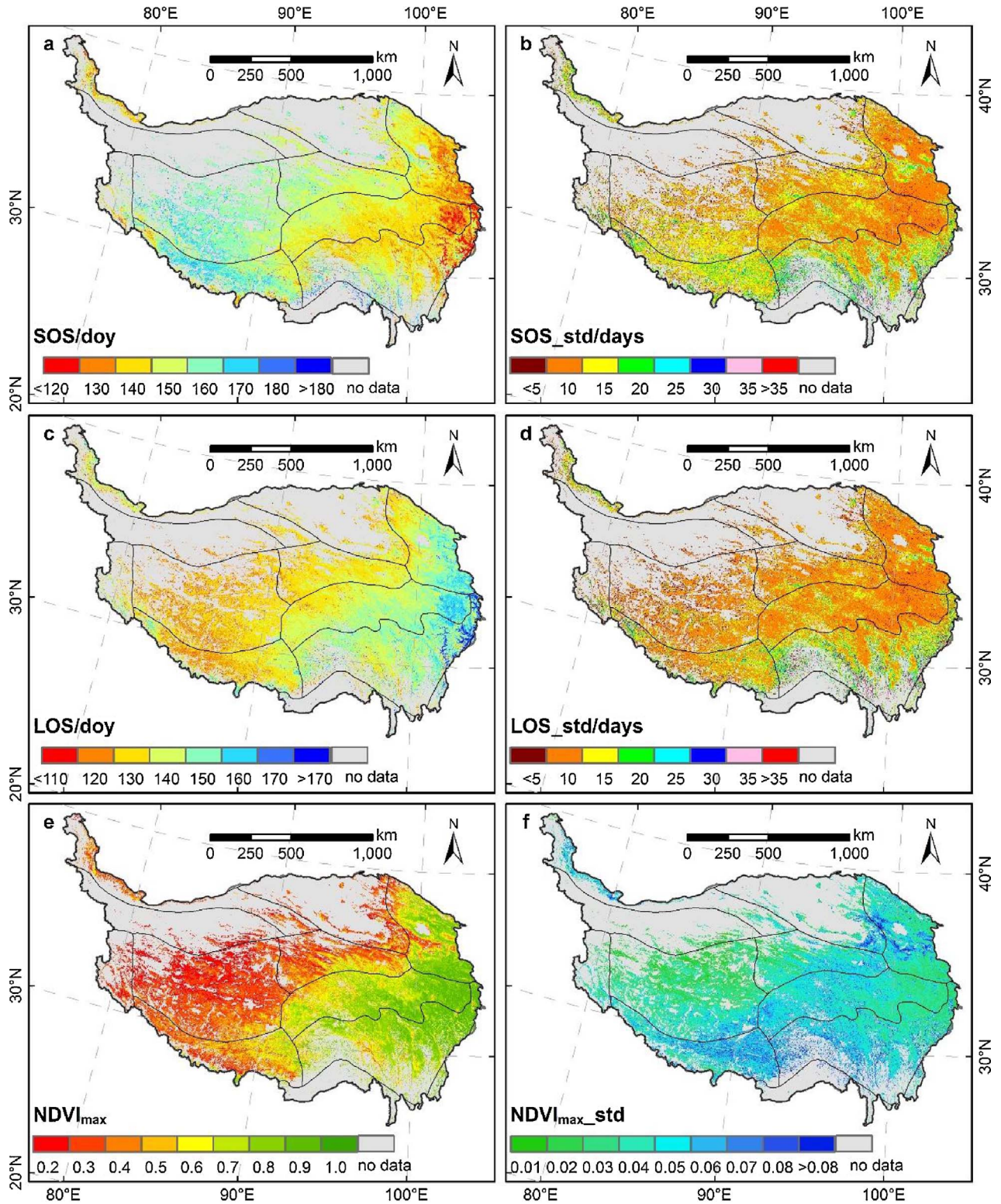

Fig. 3. Spatial distribution of mean (a) and standard deviation (b) of start of growing season (SOS). Mean (c) and standard deviation (d) of length of growing season (LOS). Mean (e) and standard deviation (f) of annual maximum $NDVI_{max}$ for 2000–2015.

and LOS, which was mainly distributed in the northeastern part and southwestern borders of TP, implying that more snow cover would increase LOS. Nevertheless, a small regions (about 2.9%) in the eastern plateau exhibited a negative relationship. SCM was positively correlated with LOS in the eastern and southwestern part of TP, while negatively correlation was observed in most part of the central plateau.

3.5. Response of $NDVI_{max}$ to snow cover phenology

We further analyzed the correlation between snow cover phenology and $NDVI_{max}$ (Fig. 7). We found that SCD had positive effects on $NDVI_{max}$ in several regions over the TP (20.7%), suggesting that prolonged snow cover duration generally will cause an increase in $NDVI_{max}$. However, we also observed a negative correlation in small

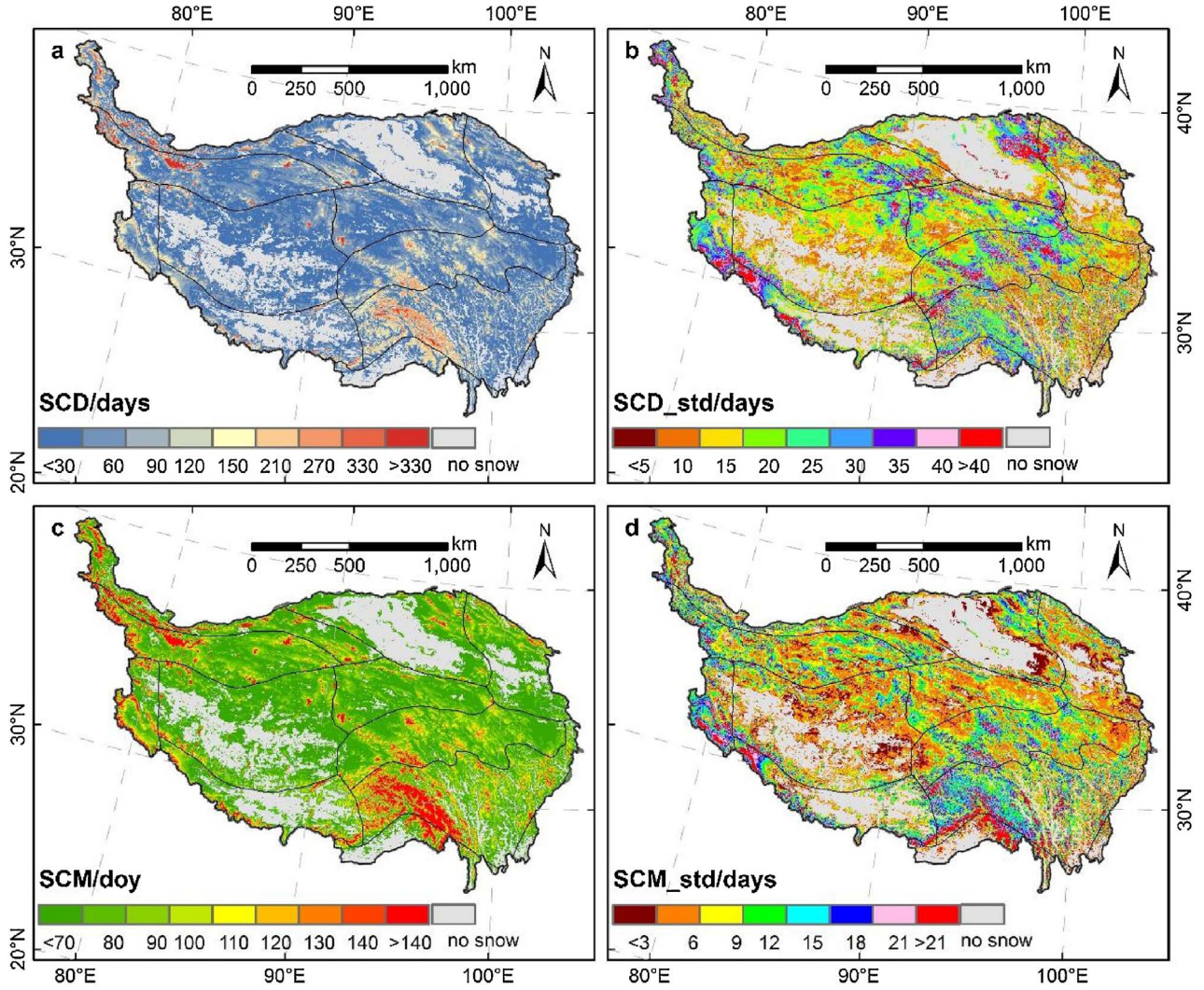

Fig. 4. Spatial distribution of mean (a) and standard deviation (b) of snow cover duration (SCD). Mean (c) and standard deviation (d) of snow cover melt date (SCM) for 2000–2015.

regions of northeast and west plateau (10.5%). SCM also had a clear influence on $NDVI_{max}$, and 12.0% of study area had significant correlation between SCM and $NDVI_{max}$, 80.8% of which was positive.

3.6. Correlations in different biomes and eco-geographical zones

In order to further investigate relationships between snow cover and vegetation phenology among different biomes, we examined the responses of SOS, LOS and $NDVI_{max}$ to SCD and SCM, respectively among four typical alpine vegetation types (Fig. 8). SCD significantly correlated ($P < 0.01$) with SOS and LOS only in alpine steppes, with R of −0.66 and 0.78, respectively, and no obvious correlation was observed for other types. We found significant positive correlation between SCM and SOS in alpine meadows ($R = 0.57$, $P < 0.05$), alpine sparse vegetation ($R = 0.81$, $P < 0.01$), and shrub ($R = 0.57$, $P < 0.05$). We also observed negative correlation between SCM and LOS in alpine sparse vegetation ($R = -0.83$, $P < 0.01$) and shrub ($R = -0.54$, $P < 0.05$). For the response of $NDVI_{max}$ to SCD, a significant positive correlation was observed in alpine meadows ($R = 0.68$, $P < 0.01$) while a weaker positive correlation was found in alpine sparse vegetation ($R = 0.51$, $P < 0.1$). In addition, all the four vegetation types showed positive correlations between SCM and $NDVI_{max}$, only differing in the level of significance.

We also analyzed relationships between vegetation growth and snow cover phenology in seven eco-geographical zones. As shown in Fig. 9, the responses of SOS, LOS and $NDVI_{max}$ to snow cover phenology varied with eco-geographical zones. We observed a significantly negative correlation between SCD and SOS, and a significantly positive correlation between SCD and LOS in cold and arid or semi-arid zones, i.e. HIC1, HIIC1, and HIIC2. For the relationship between SCM and SOS, the significant positive correlations were found in zones of HIB1 and HIIAB1 ($R = 0.68$ and 0.70, $P < 0.01$), whereas HIIC1 and HIIC2 showed significant negative correlations. For the effects of SCM on LOS, significant relationships were observed in HIB1 ($R = -0.61$), HIIAB1 ($R = -0.72$), HIIC1 ($R = 0.84$) and HIIC2 ($R = 0.71$). Furthermore, we found that SCD had significant positive effects on $NDVI_{max}$ in HIB1 and HIC1 ($R = 0.72$ and 0.83, respectively, all $P < 0.01$). In particular, all the seven zones showed positive correlations between SCM and $NDVI_{max}$, and the relationships were stronger in semi-arid and arid regions (HIC1, HIC2, HIIC1, and HIIC2) than those in humid and subhumid regions (HIB1 and HIIAB1).

3.7. Climate controls on the response of SOS, LOS and $NDVI_{max}$ to snow cover phenology

We found a strong clustering of snow cover control on vegetation dynamics over the hydrothermal gradients but responses varied substantially in different biomes (Fig. 10). In regions with precipitation less than 600 mm, SOS of all the four biomes was negatively correlated with SCD. With the increase of temperature and precipitation, the alpine

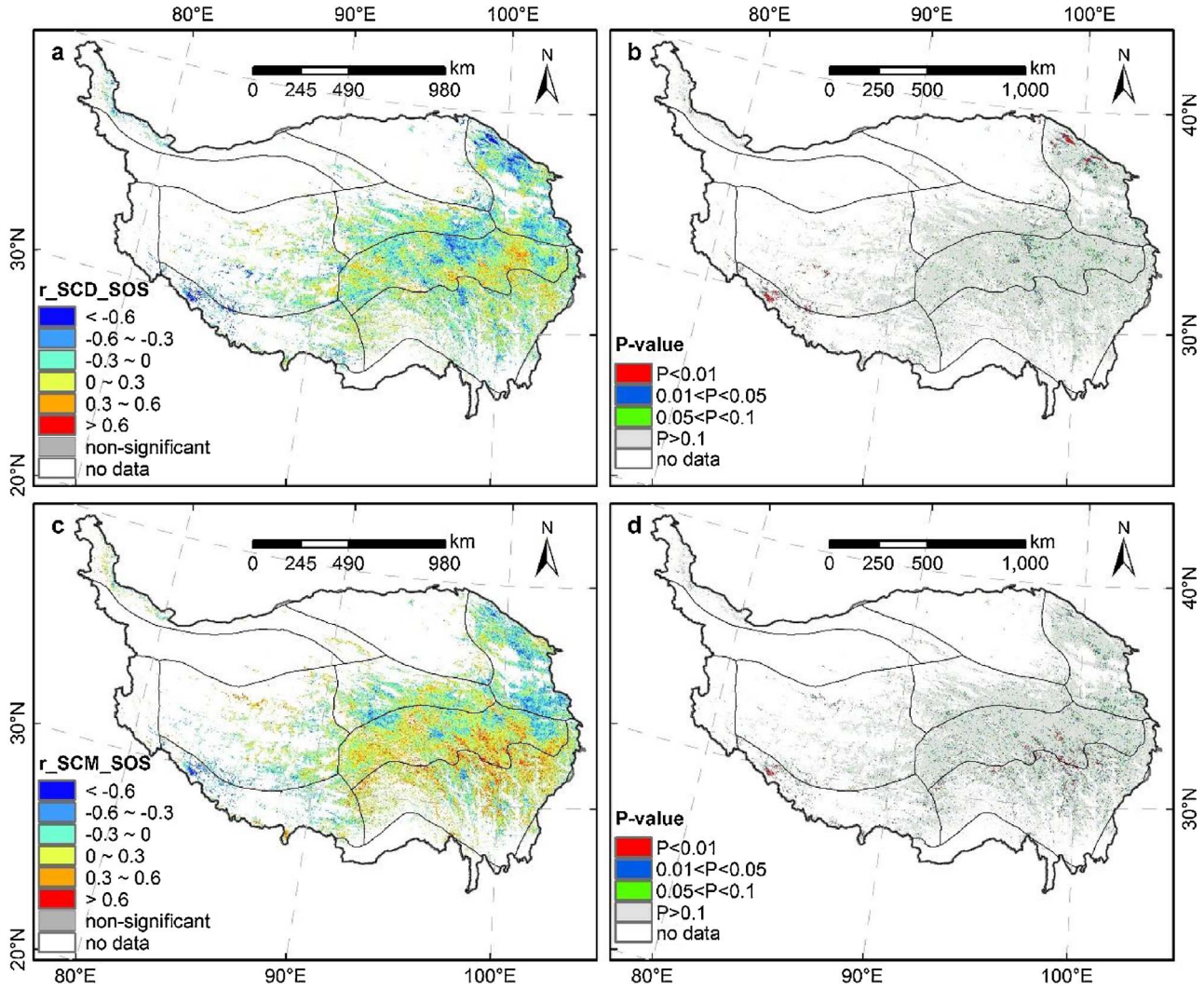

Fig. 5. Spatial patterns of correlation coefficient between start of growing season (SOS) and snow cover duration (SCD) and snow cover melt date (SCM). (a) represents the relationship between SCD and SOS, and (b) is p-values. (c) represents the relationship between SCM and SOS, and (d) is p-values.

meadows and shrub became dominant biomes. Positive correlations were mainly found in alpine meadows that located in regions with annual mean temperature between −4 °C and 1 °C and annual total precipitation between 700 and 900 mm. The responses of SOS to SCM showed large differences among the four biomes. For alpine steppes, the positive correlations were observed in the cold regions (< −1 °C), while warm areas showed negative relationships. For alpine meadows and shrub, the positive correlations were mainly occurred in humid regions with total annual precipitation higher than 600 mm. However, opposite correlations were found in warm and dry areas, where the annual mean temperature was about 6 °C and the total precipitation was around 400 mm. In comparison, the relationship between SCM and SOS in alpine sparse vegetation was less affected by hydrothermal conditions. The responses of LOS to snow cover dynamic also varied in different biomes and hydrothermal gradients. For the response of $NDVI_{max}$ to SCD, significant positive correlations were observed in the areas with total annual precipitation of 250–650 mm and lower mean annual temperature. On the contrary, areas with humid conditions showed slightly negative correlations. In general, most arid regions showed positive relationships between SCM and $NDVI_{max}$, but this relation became weaker with increasing precipitation.

4. Discussion

4.1. Influence of snow cover on vegetation phenology

Several studies have suggested that changes in spring plant phenology were principally affected by temperature (Menzel et al., 2006; Wu et al., 2016; Yu et al., 2010). Although temperature remains a key driver, our study also showed that the changes in vegetation phenology were associated with snow cover dynamics on the Tibetan Plateau. However, the response of alpine vegetation phenology to snow cover change was not constant in magnitude and direction, and varied in different regions (Figs. 5 and 6).

In the eastern part of TP, SCD showed a positive correlation with SOS but was negatively correlated with LOS. Such results agree with the previous studies that more snow cover in winter would delay spring onset date and reduce growing season (Jonas et al., 2008; Xie et al., 2017). However, we observed opposite effects of SCD on SOS and LOS in most areas of TP, implying that prolonged snow cover duration would also advance SOS and increase LOS in the following year. In general, persistent snow cover is accompanied by a higher snow depth, which can increase the amount of water used by vegetation during the subsequent growing season (Peng et al., 2010). On the other side, snow cover is also an effective insulator, and thus can protect soil from exposure to severe climatic conditions of the TP, e.g. low temperature and

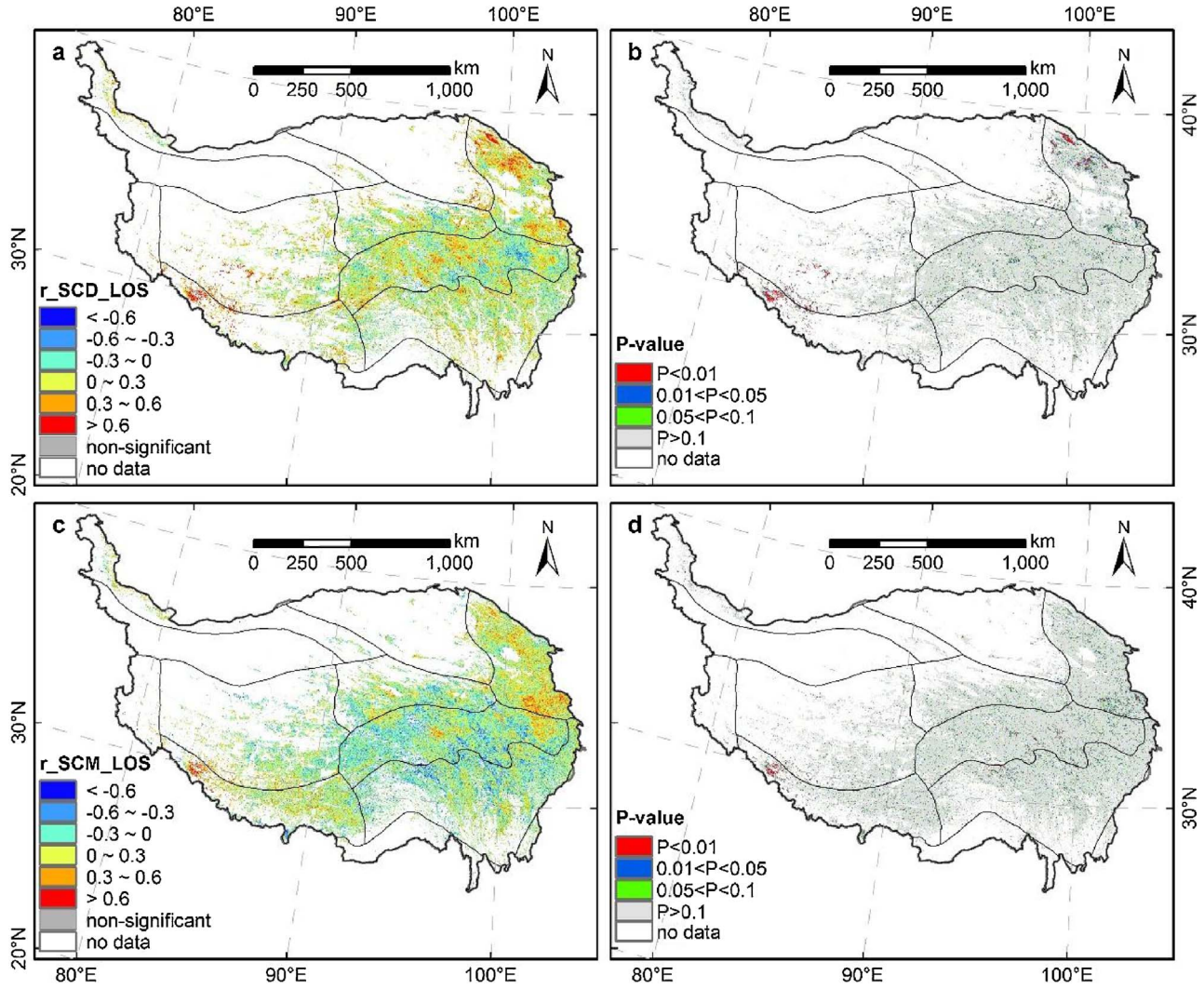

Fig. 6. Spatial patterns of correlation coefficient between the length of growing season (LOS) and snow cover duration (SCD) and snow cover melt date (SCM). (a) represents the relationship between SCD and LOS, and (b) is p-values. (c) represents the relationship between SCM and LOS, and (d) is p-values.

strong wind (Yu et al., 2013). Therefore, snow-covered areas generally have higher soil temperature than snow-free areas (Freppaz et al., 2008), which is also beneficial to the start of growing season.

On the Tibetan Plateau, snow melting date occurred from late March to middle April, and most of vegetation began to grow after late April. Thus, we can infer that SCM and SOS should have a close relationship. We did observe a positive correlation between SCM and SOS in large regions and typical biomes except for alpine steppes. This is consistent with previous founding that a later SCM would delay SOS because snow cover could block the incoming photosynthetic active radiation (PAR) (Buus-Hinkler et al., 2006; Wang et al., 2015a), and an earlier snowmelt would lead to an earlier SOS of rangeland vegetation (Paudel and Andersen, 2013). However, we also detected negative correlations in many places, suggesting that early SCM may also delay SOS, especially in temperate regions with relatively low precipitation (Fig. 9b, HIIC1 and HIIC2 zones). Earlier snowmelt may expose the soil to freezing events and decrease the soil moisture. Such mechanism has been observed in a long-term field experiment at a forest site in northeastern America (Groffman et al., 2001). We consider a similar situation might occur on the TP. Although the temperature is favorable, the vegetation cannot obtain sufficient water from snow cover if snow melts too early, which explains why warmer but drier regions showed a negative correlation between SCM and SOS. A similar situation was observed in LOS. In relatively drier areas, earlier snowmelt would delay SOS, and thus decrease LOS.

4.2. Effects of snow cover on $NDVI_{max}$

NDVI is one of the most effective indicator of vegetation vigor and ecosystem function and has been widely used to investigate changes of regional and global patterns of vegetation productivity (Alcaraz-Segura et al., 2009; Gonsamo et al., 2016a; Nemani et al., 2003; Wan et al., 2014). Several studies have observed a lag response of NDVI to rainfall since vegetation does not respond directly to rainfall amount but rather to the actual soil moisture (Paudel and Andersen, 2013; Wang et al., 2001). We found a similar lag period effect of snow cover on alpine vegetation over the TP, where a statistically significant correlation was detected between SCD and $NDVI_{max}$ (Fig. 7a). One of the reasons may be that snow cover also has an association with soil moisture (Mote, 2006). More snow cover in winter would increase soil moisture and promote the growth of alpine vegetation. In addition, relatively cold regions showed the most significant correlation, suggesting that vegetation in these areas utilizes snow cover to isolate low temperature.

The $NDVI_{max}$ also showed a positive response to SCM. Nevertheless, the positive correlation becomes stronger from wetter to dryer regions (Fig. 9f). Climate warming can cause earlier snowmelt and lengthen the summer-dry state and eventually lead to drier soil conditions (Conner et al., 2016; Potopova et al., 2016), decreasing the value of $NDVI_{max}$. In

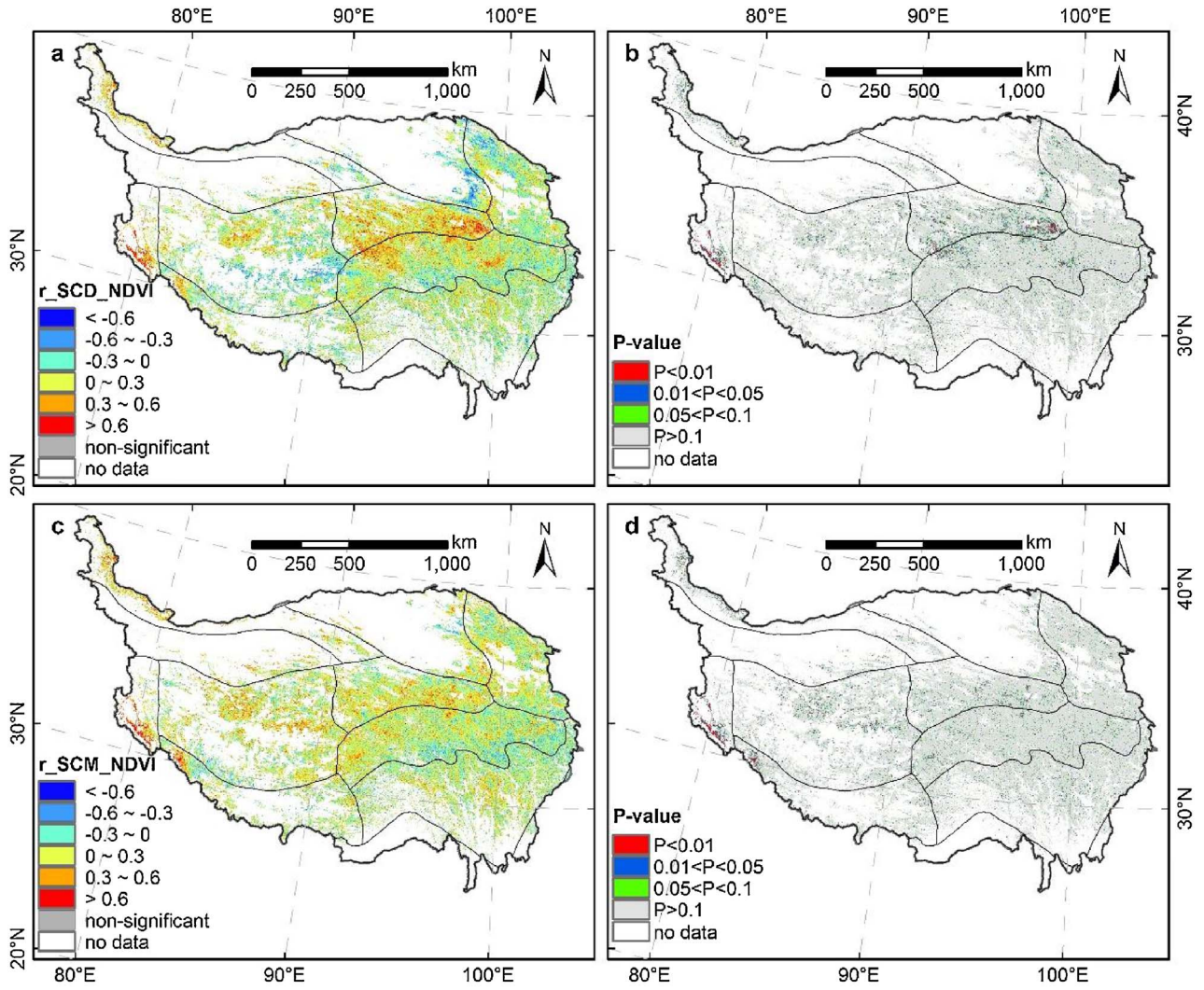

Fig. 7. Spatial patterns of correlation between $NDVI_{max}$ and snow cover duration (SCD) and snow cover melt date (SCM). (a) represents the relationship between SCD and $NDVI_{max}$, and (b) is p-values. (c) represents the relationship between SCM and $NDVI_{max}$, and (d) is p-values.

relatively higher moisture regime areas, snowmelt is not the dominant source of soil moisture. As a result, for these regions, SCM showed a weaker influence on $NDVI_{max}$.

4.3. Responses among different biomes

Responses of vegetation to snow cover dynamics showed large differences among biomes in the high latitude of Northern Hemisphere (Eugster et al., 2000). Similar phenomenon was observed on the TP (Figs. 8 and 10), indicating that the sensitivities to changes in snow cover varied in different biomes. We found the effects of SCD on SOS and LOS were more obvious in alpine steppes than for other vegetation types (Fig. 8a and c). This may be attributed to the shorter plants of steppes, which are more likely to be completely covered by snow than other taller plant forms. Therefore, snow cover can help the steppes insulate lower temperature. In addition, alpine steppes mainly occur in arid or semi-arid regions, where snow cover may provide an important contribution to soil moisture. This is reflected in the regional analysis (Figs. 9a and c, and 10a1 and c1). We also observed that the positive effect of SCD on $NDVI_{max}$ was more evident in alpine meadows (Fig. 8e). Alpine meadows generally grow in the central plateau, i.e. Golog-Nagqu high-cold zone (HIB1) and Southern Qinghai high-cold zone (HIC1), with a lower temperature but optimum soil moisture. In this case, the prolongation of snow cover duration is beneficial to the increase of soil moisture while at the same time keeps a stable soil temperature, both of which could promote the growth of alpine meadows. The results from Figs. 9e and 10e further confirm our conclusion. However, the relationship between SCM and $NDVI_{max}$ did not show a significant difference among different biomes, suggesting a consistent role of SCM on $NDVI_{max}$ across biomes.

5. Conclusions

Climate has changed significantly during the past decades, and understanding the relationship between alpine vegetation growth and snow cover is important for global change studies. Using remote sensing data for 2000–2015, we showed that snow cover phenology significantly affected the start (SOS) and length (LOS) of growing season, and the maximum of normalized difference vegetation index ($NDVI_{max}$) on the TP, but the correlations between vegetation and snow cover varied among the different biomes and thermal and moisture gradients. The correlations between snow cover duration (SCD) and SOS and LOS were much stronger in alpine steppes than other types. Most areas showed positive response of SOS to snow cover melt date (SCM), while a negative response was also found in the warm and dry areas. LOS positively correlated with SCM in areas with drier but warmer conditions, while the relatively wetter and colder regions showed negative relationships. Both SCD and SCM showed positive correlations with

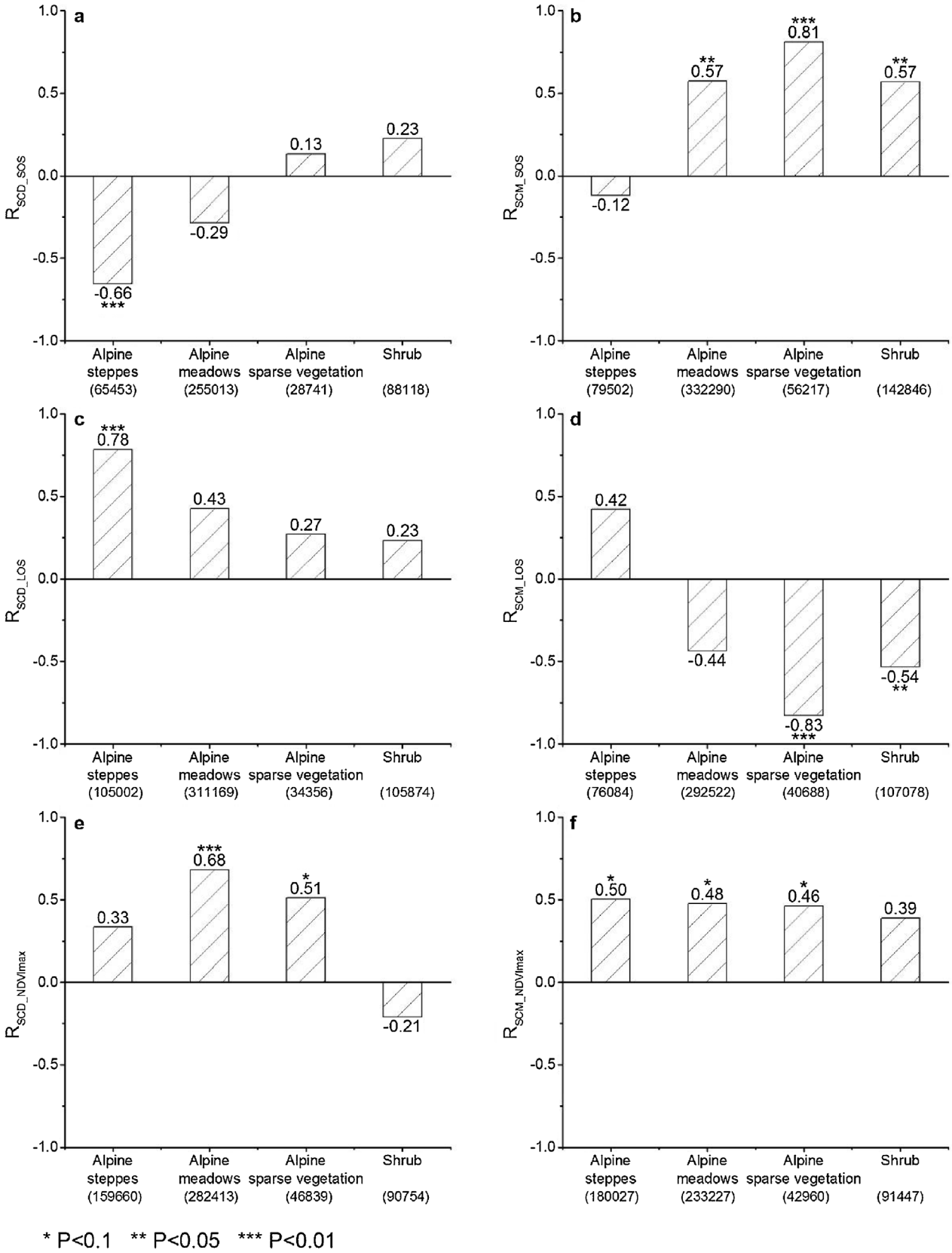

Fig. 8. Correlation coefficients between (a) snow cover duration (SCD) and start of growing season (SOS), (b) snow cover melt date (SCM) and SOS, (c) SCD and length of growing season (LOS), (d) SCM and LOS, (e) SCD and the maximum of normalized difference vegetation index ($NDVI_{max}$), and (f) SCM and $NDVI_{max}$ among four typical alpine vegetation types during the period 2000–2015. The numbers in brackets show the sample sizes of each biome.

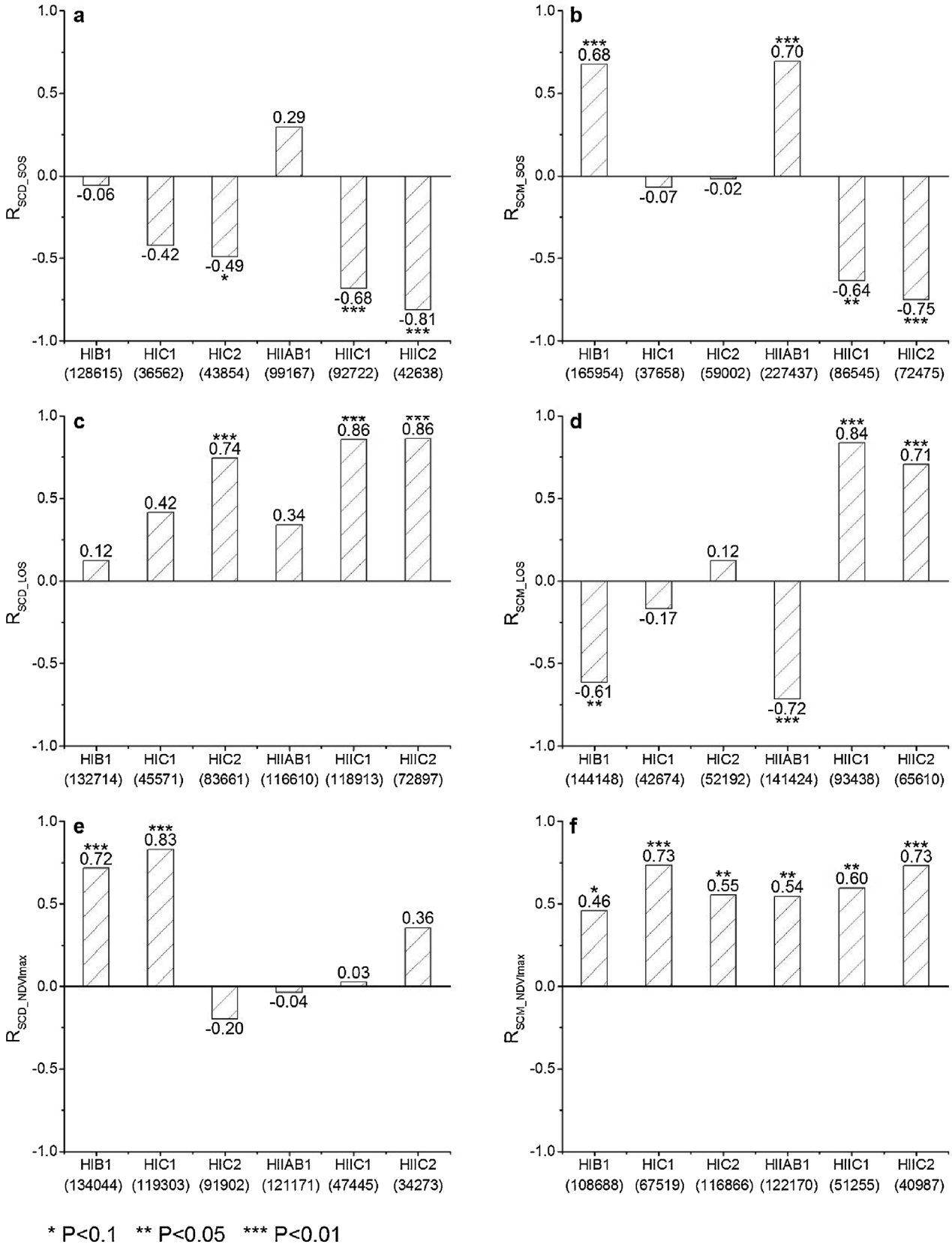

Fig. 9. Correlation coefficients between (a) snow cover duration (SCD) and start of growing season (SOS), (b) snow cover melt date (SCM) and SOS, (c) SCD and length of growing season (LOS), (d) SCM and LOS, (e) SCD and the maximum of normalized difference vegetation index ($NDVI_{max}$), and (f) SCM and $NDVI_{max}$ among six eco-geographical zones during the period 2000–2015. The numbers in brackets show the sample sizes of each eco-geographical zone.

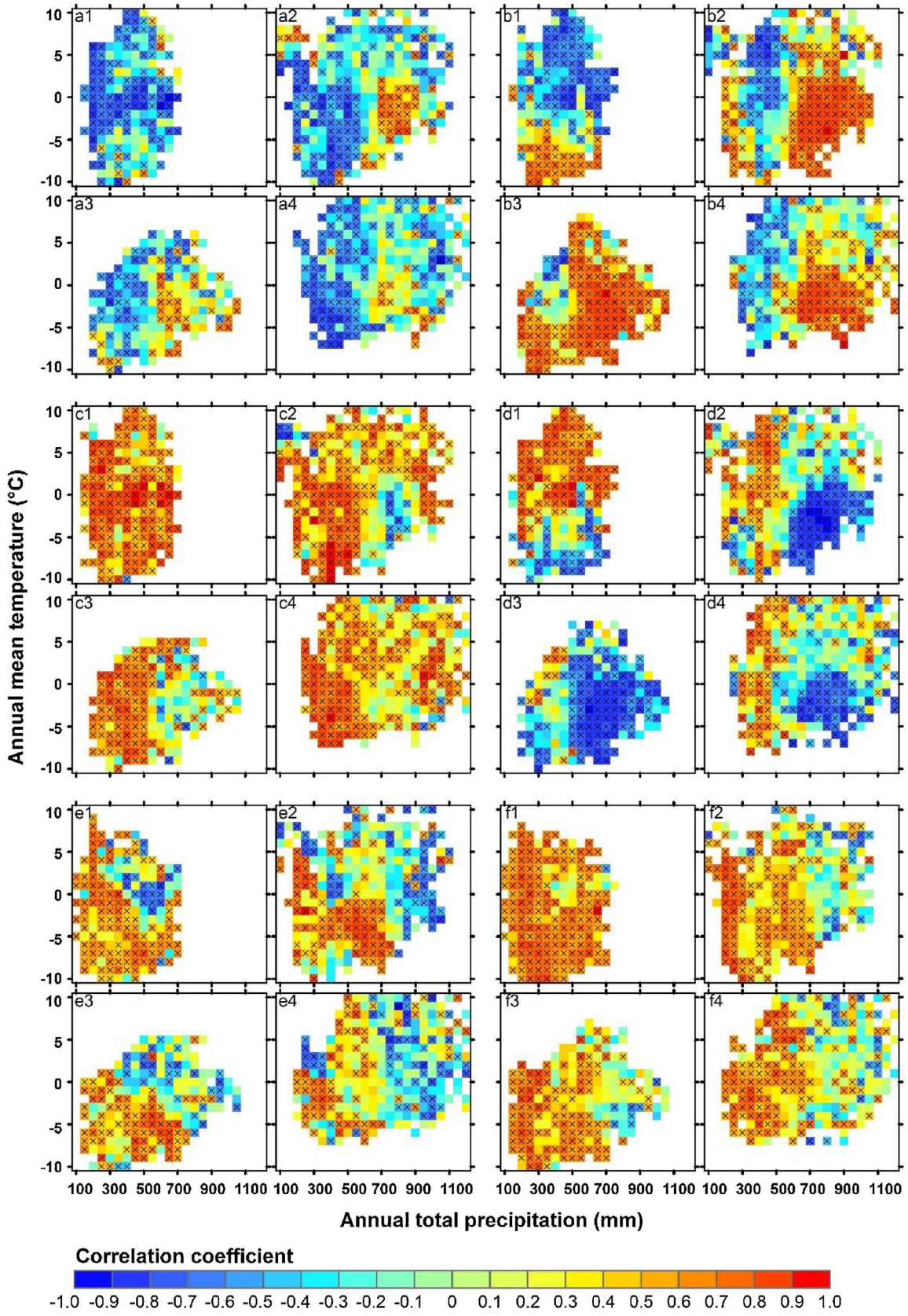

Fig. 10. Variations of correlation coefficients between snow cover phenology and alpine vegetation growth along temperature and precipitation gradients for each biome over the Tibetan Plateau from 2000 to 2015. The letters a–e represent the correlation coefficients between snow cover duration (SCD) and start of growing season (SOS), snow cover melt date (SCM) and SOS, SCD and length of growing season (LOS), SCM and LOS, SCD and the maximum of normalized difference vegetation index ($NDVI_{max}$), and SCM and $NDVI_{max}$, respectively. The numbers 1–4 represent alpine steppes, alpine meadows, alpine sparse vegetation, and shrub, respectively. The crosses (×) indicate the pixels with significant correlation ($P < 0.1$).

$NDVI_{max}$, but increase in soil moisture supply weakened the relationship. Our results reveal the important role of snow cover variability on vegetation growth on TP, and how challenging it is to accurately characterize the changes of alpine vegetation with only temperature and precipitation in most current ecosystem models. In addition, data with higher spatial resolution and longer time range maybe considered to more accurately reflect the interactions between vegetation dynamics and snow cover in alpine ecosystems in the future.

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